Book Section:

Dawson, J F orcid.org/0000-0003-4537-9977, Hope, D C, Panitz, M et al. (1 more author) (2008) WIRELESS NETWORKS IN VEHICLES. In: 2008 IET Seminar on Electromagnetic Propagation in Structures and Buildings. IET .

WIRELESS NETWORKS IN VEHICLES

J F Dawson*, D C Hope*, M Panitz†, C Christopoulos†

***Dept of Electronics, University of York, York, YO1 5DD, UK, e-mail: jfdawson@theiet.org**

† School of Electrical and Electronic Engineering, University of Nottingham, UK

Keywords: Zigbee, Wireless Network, Vehicle.

Abstract

Wireless networks in vehicles have the possibility to reduce wiring costs and weight, and allow for more flexible installation of electronic systems. However the radio propagation environment inside vehicles such as aircraft presents unique challenges to the operation of wireless networks. An airframe or other vehicle body can be considered a set of coupled cavities. The cavities present a potentially high-Q reverberant behaviour which results in large delay spreads which can cause poor performance in digital radio systems. The presences of multiple, coupled cavities exacerbate the problem. Coupling between cavities is not controlled in vehicle designs and must be considered if radio connectivity is to be ensured. This paper will describe research being carried out at the Universities of York and Nottingham in measuring and modelling the performance of wireless networks in reverberant environments using the Zigbee system as an example.

1 Introduction

Wiring in an aircraft contributes significant weight to the airframe, the associated connectors complicate maintenance and reduce reliability. A typical passenger aircraft (e.g. Boeing 747) contains over 220,000 metres of wire weighing 1600kg [1]. One of the main causes of the Airbus A380 production delays has been due to installation of the signalling cables [2]. Increased flexibility for initial and future modifications can be achieved by the use of wireless interconnectivity [3]. Protection is required to prevent damage to wiring harnesses from lighting strike and other electromagnetic interference. Wiring looms are also vulnerable to ageing and battle damage, whereas a wireless system may continue to function as long as the communicating units are not damaged. Whilst it is likely to be impossible to replace the entire wiring loom, the ability to connect to a number of sensors/actuators by wireless means may offer significant savings in weight, improved resilience to damage, and lightning strike.

This paper describes the unique propagation environment, in vehicles structures, and gives an overview of commercial off-the-shelf (COTS) radio systems which might be considered for use in wireless networks within vehicles. Some initial results describing the performance of the Zigbee [4] radio system in a reverberant environment are then presented.

2 In vehicle propagation environment

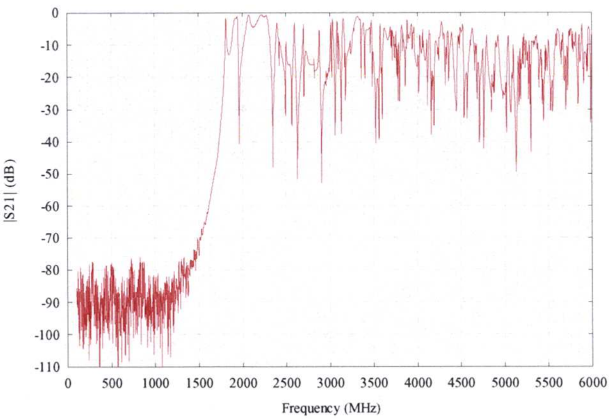

Figure 1: Coupling between two monopoles in a closed 96.5mm diameter conducting cylinder

Most aircraft and many other vehicles could be described as a collection of cavities, fabricated from conducing materials (metal, or carbon fibre composite) and coupled by apertures and wiring looms. The cavities are also populated with contents such as electronic, and mechanical systems, fuel, wiring, pipes and ducts. Some areas will also have windows, people, and furniture.

Propagation in conducting cavities is dependent on the cavity geometry and can vary rapidly with frequency. Figure 1 shows the coupling between two monopoles in a closed conducting cylinder. Two common features of cavity coupling can be seen. The coupling below 1850 MHz is very small due to the cut-off frequency of the first waveguide propagation mode. The cut-off frequency of a hollow waveguide corresponds to the frequency where the largest cross-sectional dimension is equal on half of the wavelength. Above 1850 MHz the coupling varies rapidly with frequency due to the resonances which are a consequence of reflections from the closed ends of the cylinder. The cut-off frequency corresponds to the frequency at which the largest dimension of the cross-section is half a wavelength. As the frequency increases, other higher order propagating modes become possible, and the number of resonant modes increases rapidly. The differing propagation velocities and dispersion in the individual waveguide modes coupled with the decay times of the resonances, which are dependent upon their Q-factors, produce a propagation channel with a large delay spread and the associated rapid variation in the amplitude of coupling with frequency. The behaviour of closed cavities has been analysed in detail in the literature relating to reverberation chambers and can be found in the work of Hill and colleagues from NIST [5].

Limited data is available on the propagation in real airframes. We are planning to perform some trial measurements on the HERTI UAV, as part of the ASTREA programme, and possibly other airframes in the near future. However we have used our reverberation chamber to test the performance of a Zigbee radio system and this is described in Section 4.

3 Radio systems for sensor and control networks

Here we review briefly the various radio technologies of relevance to sensor and control networks in vehicles both in terms of the generic technology and the COTS systems available as most of the relevant radio systems are available in integrated form.

3.1 Modulation

In order to achieve realistic data rates in dispersive environments, and to improve robustness to interference, most modern digital radio systems use some form of spread-spectrum technology or transmit on multiple sub-carriers. The modulation scheme chosen has a direct bearing on other performance factors such as the power consumption and complexity of the radio system. Simple direct sequence spread spectrum systems such as that employed by the Zigbee standard [4] require only simple hardware and signal processing and therefore can operate at low power and easily be switched on and off on short time scales to further conserve power. More complex signal processing is required by schemes with multiple sub-carriers such as the orthogonal frequency division multiplexing (OFDM) used in current wireless LAN standards [6]. The higher complexity of OFDM systems means higher power consumption and significant start-up and shut-down times so that network nodes cannot easily power down for short periods. If we wish a network to be truly wireless then low power systems are attractive as they can be operated under battery power or using small amounts of scavenged energy.

3.2 Network structures

Many network topologies are available. Wired networks tend to be constrained to bus and star, tree and ring-like topologies which are vulnerable to failure of connections. Radio networks can be used in mesh, or fully connected configurations which are potentially robust against the loss of individual links or nodes. It would therefore be advantageous to use a wireless standard that allows robust interconnectivity by multiple routes.

3.3 Power considerations

For wireless sensor networks low power operation is advantageous, though for control of actuators where a significant source of power is required for the actuator, this may not be important. It is possible that low powered wireless sensors could operate from energy scavenged from thermal gradients, vibration, or air-flow in the vicinity. A wide range of energy scavenging techniques are discussed in [9].

3.4 Safety and Security

Any wireless system used in control and sensor systems should be robust against interference and eavesdropping. A system capable of operating with some form of encryption is highly desirable. Most of the modern wireless systems incorporate some form of encryption, though some have been proven simple to break [10]. It is also important that any wireless system be safe and reliable enough for use in airborne systems.

3.5 COTS Radio systems

A wide range of COTS radio systems are available including Zigbee [4], Bluetooth [11], WiFi [6], and recently a number of UWB [12] implementations. We chose to evaluate the performance of the Zigbee system because it is able to support low power operation, encryption, and can be configured in mesh, star or tree network configurations. The data rate of 250kbit/s is lower than most of the other systems but is adequate for many sensor and actuator control applications.

4 Performance of the Zigbee system in a reverberant environment

A Zigbee system was tested in the reverberation chamber at York.

4.1 Measurement set up

A mode stirred or reverberation chamber is a resonant cavity operated in a frequency range where many resonant modes are excited, with a mechanical device for 'stirring' the field inside the chamber. Reverberation chambers have been found useful for communications measurements because they can replicate a Rayleigh or Ricean fading environment which changes as the stirred is moved [5]. It may be used to emulate multi-path propagation effects as the many reflections over a short distance can cause a time delay such that there is phase shift that is high relative to the wavelength, just as a few reflections over a long distance can. The dimensions of the larger chamber used are 4.7x3.0x2.37m. There were no additional noise sources and the receiver noise figure is given by the manufacturers as approximately 10dB at room temperature. Where reference is given to the smaller chamber this has dimensions of 0.6x0.7x0.8m. In order to control the energy in the chamber and therefore the Q-factor and delay spread, AN79 absorber was added in varying amounts.

The channel impulse response and ZigBee performance were measured in the reverberation chambers with the stirrer static, in a number of different positions and with the stirrer in motion. Radio absorptive material was introduced into the chambers to control the Q-factor.

4.2 Obtaining the channel response

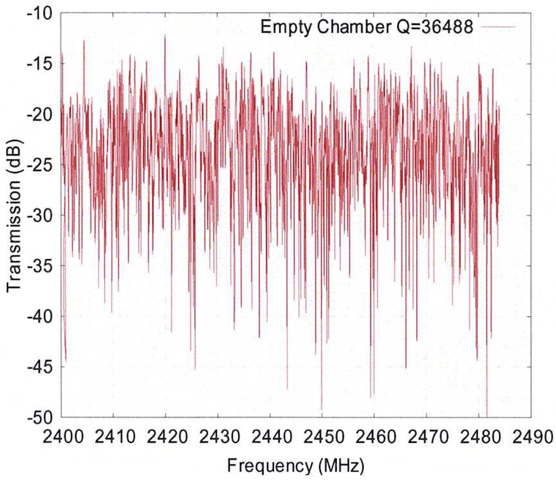

Figure 2: Coupling between two monopoles in two ZigBee quarter wave antennas in the large reverberation chamber empty (no absorber)

An Agilent E5071B network analyser was used to measure the frequency response of a channel between the antenna terminals in the form of the S21 network parameter. The Zigbee standard specifies a number of channels over an 85MHz bandwidth. The channels themselves are spaced at 5MHz intervals and partially overlap. Measurements were taken over a bandwidth of 84MHz which covers the majority of the ZigBee channels, and was picked for numerical convenience when doing post processing. Measurements were taken with a 0.06MHz step size from 2.4GHz to 2.484GHz resulting in a total of 1401 data points.

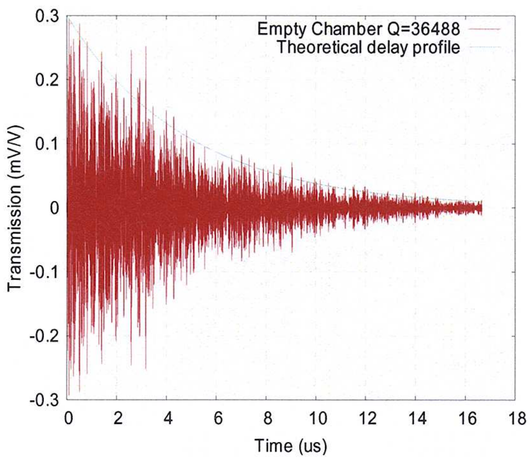

Figure 3: Coupling between two ZigBee quarter wave antennas in the large reverberation chamber, empty.

Each measurement over the frequency range was taken with the stirrer static at a particular position. A number of these measurements were taken at different stirrer positions in order to obtain channel statistics, with the number of measurements depending on the particular experiment. In order to determine the time response of the channel the data was first padded with zeros up to 2.4GHz in 0.6MHz steps. A discrete Fourier transform was then applied to produce the channel impulse response.Given the need for delay spread to be within 1/5 of the symbol time this would suggest that a high error rate will occur up to the point where delay spread is less than 3 μs for the ZigBee system and therefore the Q-factor should be kept under 5000 in any environment in which it might be used. The delay spread in an office environment for which the COTS systems are designed is assumed to be less than 200ns. The large delay spread in the time domain implies a rapidly varying frequency response. Figures 2 and 3 show the frequency and time response of the large reverberation chamber. From the frequency response we determined a Q-factor of 36488. Figure 4 shows the measured delay spread as a function of chamber Q-factor (frequency response values are used) and shows that it correlates well with the chamber time constant derived from the Q-factor though it is about four times larger.

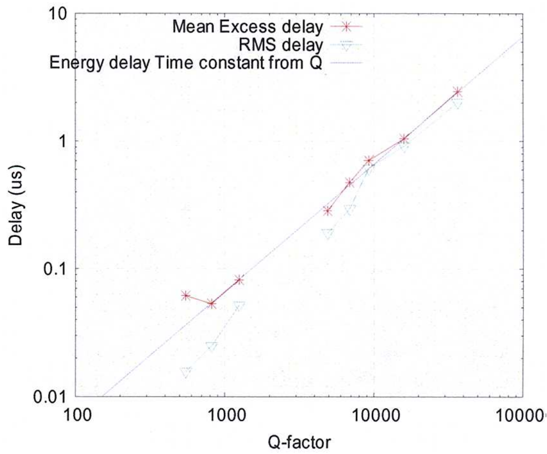

Figure 4: Delay spread as a function of Q-factor compared with chamber(energy) time constant. The measured delay spread is about one time constant as expected.

4.3 Packet error rate measurements

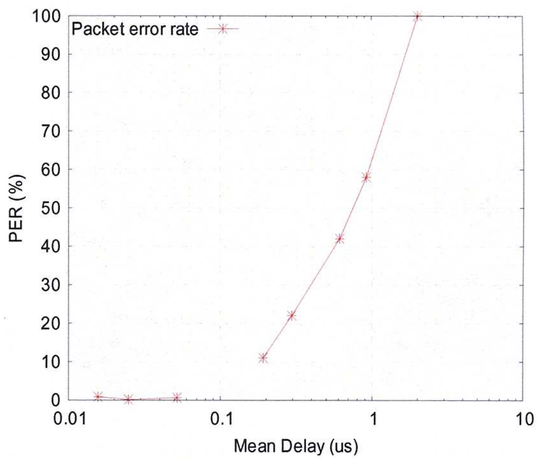

Figure 5: Measured Zigbee packet error rate as a function of mean delay spread.

Due to limitations of the test API provided by the manufacturer of the Zigbee receivers it was not possible to obtain bit error rates for the system. Packet error rates were averaged over 10 different stirrer positions. There was a stirrer rotation of 3 degrees between each position. This was selected because there is low correlation between the coupling measured at different positions with this separation ensuring independent measurements. In the case of the small chamber the stirrer was moving continuously at a slow rate as a stepper motor was not available. It can be seen from Figure 5 that ZigBee generally functions reliably when the Q-factor is less than 5000 (delay <0.3μs) but it won't work

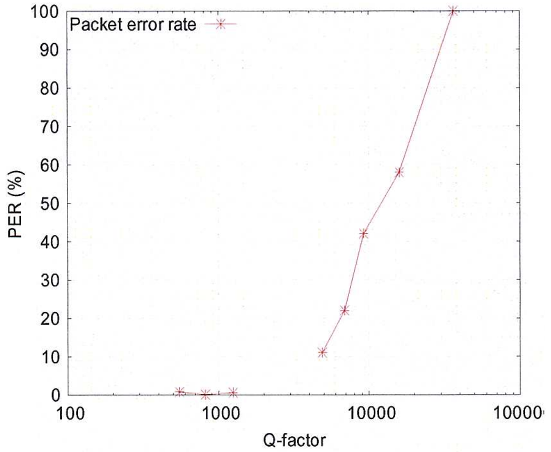

Figure 6: Zigbee packet error rate as a function of Q-factor.

Whilst Figure 5 shows packet error rates with the mode stirrer stationary against mean delay, Figure 6 shows the packet error rate against Q-factor. Unfortunately we have not yet been able to obtain data points for Q-factors in the 1-3000 range.

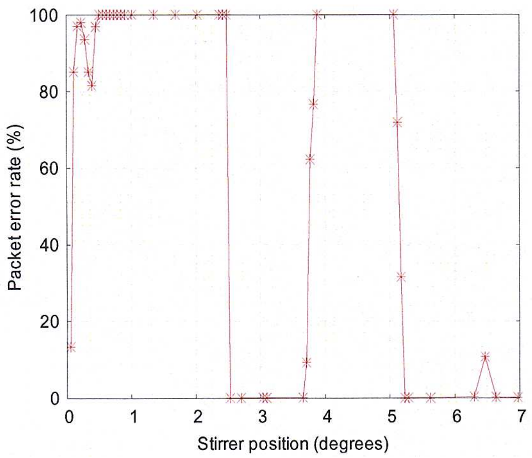

Figure 7: Zigbee packet error rate as a function of stirrer position at a Q-factor of 7000.

Whilst the measurements of Figures 5 and 6 were taken with the stirrer stationary, the effect of stirrer motion was expected to be significant. In Figure 7 It can be seen that the rapid fading caused by the movement of the stirrer significantly increases the packet error rate. Figure 7 shows that the packet error rate can change rapidly with stirrer position (static stirrer) and can change from 100% transmission to 100% loss with about 1mm movement at the periphery of the stirrer (0.05 degrees).

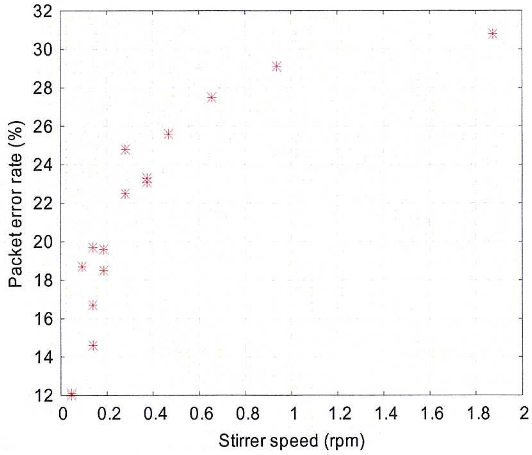

Figure 8: Zigbee packet error rate as a function of stirrer speed at a Q-factor of 7000.

Performance of Wifi in a reverberant environment

We have also been able to perform some preliminary tests of a simple point-to point (Ad-hoc) Wifi network in the reverberation chamber at York. The 802.11b modulation scheme was used, it has a transmission rate of up 11Mbit/s and has a complex encoding scheme with a chip-rate of up to 11Mchip/s using some spreading of the data, however it is able to switch between several transmission rates and methods as the channel changes. Packet error rates and throughput where measured for UDP packet transmission.

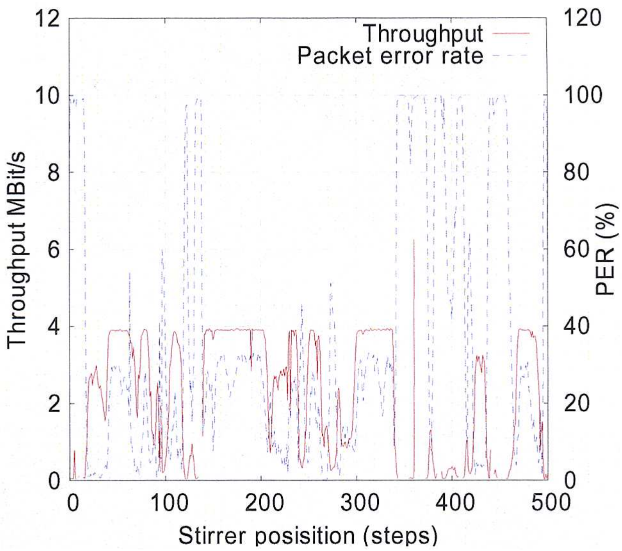

Figure 8: Wifi Packet error rate and throughput at an average Q-factor of 1451

Figure 8 shows how the performance of a Wifi link varied with stirrer position in the reverberation chamber with a Q-factor of 1451 corresponding to a mean delay spread of 0.1 µs. One stirrer step corresponds to a movement of approximately 1 mm at the periphery of the stirrer. Again it can be seen that relatively small movements of the stirrer can produce large changes in performance of the Wifi system. Another older Wifi system had a significantly poorer performance in this test, with occasional permanent link failures

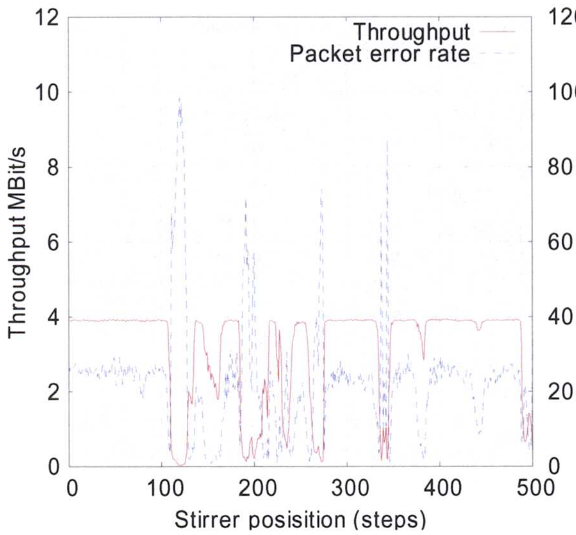

Figure 9: Wifi Packet error rate and throughput at an average Q-factor of 573

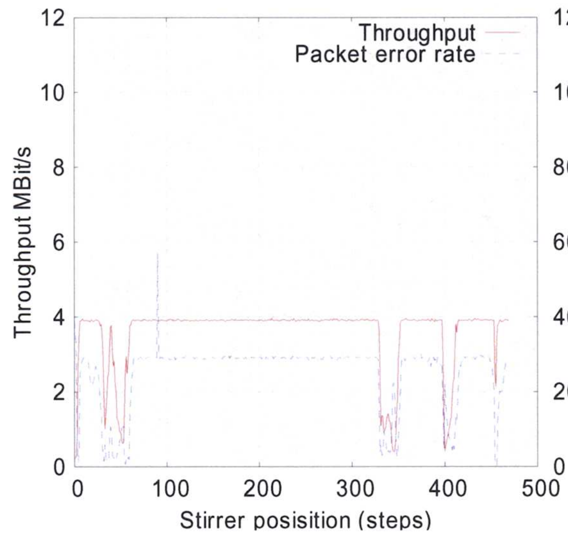

Figure 10: Wifi Packet error rate and throughput at an average Q-factor of 144

Figure 9 shows how the performance of a Wifi link varied with stirrer position in the reverberation chamber with a Q-factor of 750 corresponding to a mean delay spread of 0.05 µs. It can be seen that although the performance has improved considerably there are still some stirrer positions where the packet error rate approaches 100%.

Figure 10 shows the time varying performance of the Wifi link in an office environment for comparison.

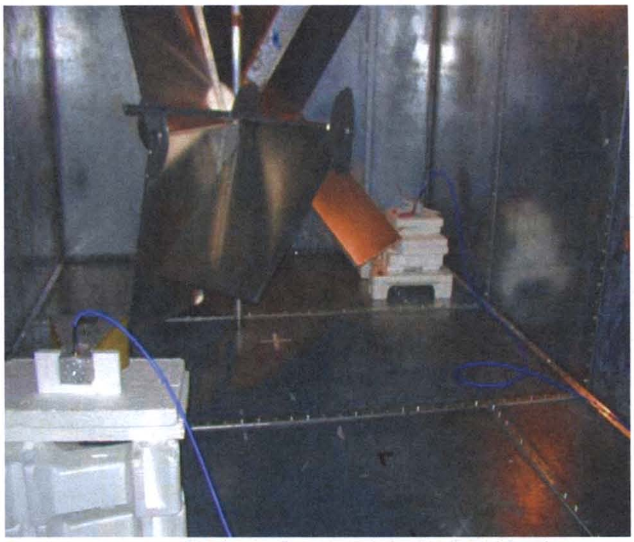

Figure 11 York's large (4.7x3.0x2.37m) reverberation chamber showing horn antennas used for Q-measurement

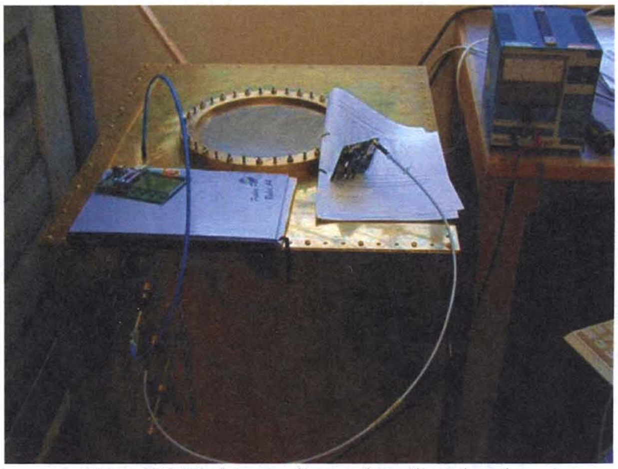

Figure 12 York's small reverberation chamber

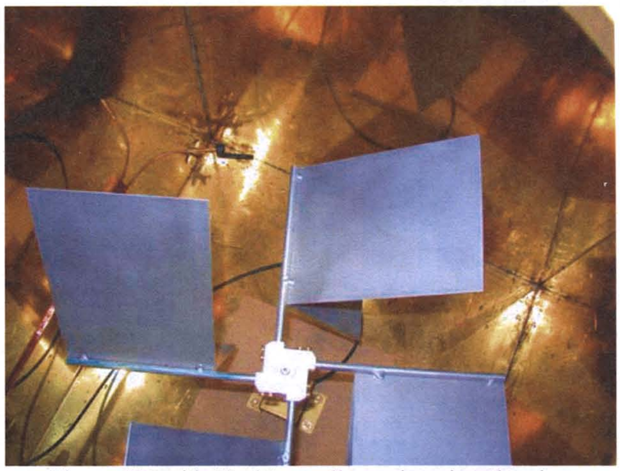

Figure 13 Inside York's small reverberation chamber

References

[1] C. Furse, R. Haupt, "Down to the Wire", IEEE Spectrum, vol. 38, no. 2, pp. 34-39, 2001

[2] J. Prendergast, "Airbus Industries - Caught Between Several Rocks and a Hard Place", The European Journal, vol. 14, no. 3, pp. 14-18, 2007.

[3] G Studor, "Fly-by-Wireless: A Revolution in Aerospace Vehicle Architecture for Instrumentation and Control", CANEUS "Fly-by-Wireless" Workshop, 27-28 Mar. 2007, Grapevine, TX, United States

[4] Zigbee Alliance, "Zigbee specification", Version 1.0, December 14th 2004, available from: http://www.zigbee.org/en/index.asp.

[5] D. A. Hill, "Plane-wave integral representation for fields in reverberation chambers," IEEE Transactions on Electromagnetic Compatibility, vol. 40, pp. 209–217, Aug. 1998.

[6] IEEE Computer Society, "IEEE Std 802.11g™-2003, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications, Amendment 4: Further Higher Data Rate Extension in the 2.4 GHz Band", IEEE, 27 June 2003, available from: http://standards.ieee.org/getieee802/download/802.11g-2003.pdf

[7] Wikipedia, "Network topology", 21 July 2008, http:/en.wikipedia.org/wiki/Network_topology

[8] Wikipedia Commons, "NetworkTopologies.png", retrieved 21 July 2008, http://commons.wikimedia.org/wiki/Image:NetworkTopologies.png

[9] J A. Paradiso and T Starner ,"Energy Scavenging for Mobile and Wireless Electronics", IEEE Pervasive Computing, January-March 2005, pp 18-27

[10] Wired Equivalent Privacy, Wikipedia, http://en.wikipedia.org/wiki/Wired_Equivalent_Privacy, retrieved 23 July 2008

[11] Bluetooth® SIG, Inc., "Bluetooth® Specification", 05 November 2003, available from http://www.bluetooth.com

[12] Wikipedia, "Ultra-wideband", retrieved 23 July 2008, http://en.wikipedia.org/wiki/Ultra-wideband

[13] "FLAVIIR integrated programme in Aeronautical engineering", *EPSRC grant GR/S71552/01*, see http://www.flaviir.com/